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博 士 学 位 论 文

海岸带地下水循环与海底地下水排泄研究

Study on Groundwater Cycle and Submarine Groundwater Discharge in the Coastal Zone

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摘　要

海岸带地下水循环和海底地下水排泄是全球水循环的重要组成部分，近年来成为陆-海相互作用研究的主要内容之一。海底地下水排泄不单是一个水循环过程，还是一个地球化学循环过程，其输送大量营养盐、碳、金属等物质到海洋中，在海洋物质收支平衡中具有重要意义。本论文的主要目标是了解福建沿海的地下水循环特点和地下水入海通量，为此，在福建省科技计划项目和国家自然科学基金的资助下，选择厦门五缘湾、闽江河口和漳州前湖湾为研究区域，通过现场观测、调查和取样，并采用同位素示踪技术、电法探测和水文地球化学等研究方法和手段，对水体滞留时间、海底地下水排泄量、河水与海水混合速率、地下水与河水补排关系、地下水、河水及海水的混合比例、不同类型含水层中地下水循环特点、海底泉成因、海岸带地下水循环模式等问题开展了研究。

（1）厦门五缘湾

五缘湾是厦门岛内的一个小海湾，其海岸属于砂质类型海岸，海岸带主体由未固结的晚更新世海积-冲积物和全新世海积物组成。五缘湾的水体滞留时间和地下水入海通量是重点研究内容。

借助224Ra和226Ra半衰期的差异，利用224Ra和226Ra比值计算得到五缘湾水体的表观年龄在0.6~2.4 d之间，平均滞留时间为1.4 d，其中湾顶水体滞留时间较长。该结果与用纳潮量方法计算的滞留时间1.2 d比较接近。

地下水和海水中224Ra与226Ra活度的比值特征表明，输入五缘湾的地下水，70.2%源自冲积层中的孔隙潜水，29.8%源自海积层中的孔隙潜水。通过构建224Ra和226Ra的质量平衡模型（箱式模型），计算获得地下水输入的224Ra和226Ra通量分别为5.17×106 Bq/d和5.28×106 Bq/d，转化为海底地下水排泄量为4.16×105 m3/d和4.73×105 m3/d。

（2）闽江河口区

闽江河口区是一个基岩海岸和砂质海岸共存的海岸类型，河水、地下水和海水三者相互作用明显。通过枯水期和丰水期的调查和取样，重点对河水与地下水的补排关系、河水与海水的混合速率、河水、地下水及海水的混合比例，以及地下水入海通

量进行了研究。

河流悬浮颗粒上224Ra和 226Ra的解吸程度随盐度升高而增大，在盐度17.0~18.0时，224Ra和 226Ra基本上达到完全解吸。当河流悬浮颗粒上的224Ra和 226Ra完全解吸以后，混合水中的224Ra和 226Ra活度随着离岸距离的增加而呈指数衰减，由此计算获得涨潮时段内河水与海水的混合速率为140.2~142.5 m/h。

水样的δ2H、δ180散点图较好地反映出地下水和河水的起源与演化，以及地下水与河水的相互补排关系。在枯水期，闽江南岸地下水接受当地降水补给后又经历了一定的蒸发作用，而闽江北岸地下水接受当地降水补给后基本上没有受到后期蒸发作用的影响；在丰水期，闽江两岸地下水均接受了大气降水的充分补给，蒸发作用轻微。无论枯水期还是丰水期，闽江河水都是接受两岸地下水的补给；在枯水期，闽江南岸地下水经历一定的蒸发作用后再补给河水，而在丰水期两岸地下水基本上接受降水补给后又快速补给河水。

以河水、地下水和海水为端元构建三端元混合模型，计算获得丰水期闽江河口区河水、地下水和海水的混合比率分别是34.2%、10.3%和55.5%。以闽江的月平均入海径流量为依据，计算获得丰水期和枯水期闽江河口区地下水的入海通量分别是58.1×106 m3/d和7.5×106 m3/d，前者约是后者的7.7倍。进一步计算获得丰水期地下水输入闽江河口的溶解无机氮、活性磷酸盐、溶解性硅酸盐通量分别是12.4×106 mol/d、0.5×106 mol/d和10.8×106 mol/d。

（3）漳州前湖湾

前湖湾是比较典型的海岸沙丘发育的砂质海岸，岸线较为平直，海滩平坦宽阔，非常有利于研究海岸带的地下水循环。而且，前湖湾在潮间带发育海底泉，这在国内是很少见的，泉水的来源至今还是个迷。为此，通过调查和取样对海岸带地下水循环特点和模式、海底泉的形成开展了研究。

近岸海积层-风积层互层构成的含水层系统，主要接受降水的垂直补给，含水层渗透性和富水性均很好，水循环速度较快，直接向海域排泄。水化学成分（Cl/Br比、Ca/Mg比、Ca/SO4比）表明，该含水系统孔隙水中仍部分保留海侵时期的海水组分特征。表层风积物中的孔隙水，受现代海水的影响，表现出部分海水的特征。受人为过量开采地下水的影响，近岸局部地段出现不同程度的海水入侵现象。滨海平

原冲洪积层中的孔隙水，径流比较缓慢，溶滤作用和蒸发浓缩作用同时存在。风化残积层中的裂隙-孔隙水，其化学组成变化很大，水循环速度明显受局部地形的影响和控制。新近纪玄武岩-砂岩组裂隙-孔隙水，阳离子Na^+、Mg^{2+}和Ca^{2+}毫克当量百分数都超过25%，阴离子则以HCO_3^-为主，说明其水循环速度远高于冲洪积层孔隙水和风化残积层裂隙-孔隙水，这与其所处地势较高，以及玄武岩垂直裂隙发育、砂岩呈半固结状等有直接关系。

高密度电法揭示海底泉在海滩上的出露直径约为5.5~6.0 m，泉眼处垂向上的延伸深度约是2.5~3.0 m；海底泉的补给路径不与海岸线垂直，而是偏向其西北方向，该方向与基底燕山期侵入岩中断裂带的发育方向比较吻合。

海底泉与新近纪玄武岩-砂岩组裂隙-孔隙水化学组成的相似性、海底泉异常高的^{222}Rn活度等证据表明，海底泉的补给区可能是位于莲花山一带的新近纪玄武岩-砂岩含水岩组，该含水岩组的裂隙-孔隙水通过下伏燕山期花岗岩的断裂带输送给海底泉。

潮间带孔隙水盐度分布很不均一，明显受到海底泉和陆源淡水排泄的影响。垂直岸线的潮间带孔隙水盐度分布特征表明，潮汐泵海水小循环、盐水楔海水大循环和陆源地下淡水排泄共同构成了前湖湾近岸基本的水循环模式，海底泉排泄使得该水循环模式变得复杂化。

潮间带浅表层（70 cm以浅）孔隙水的主要离子和营养盐组成表明，潮间带孔隙水循环速度很快，其地球化学过程比较简单，化学反应微弱，主要是地下淡水与海水的物理混合作用。

综上所述，福建省海岸带类型比较复杂，不同类型海岸带的地下水循环特点和海底地下水排泄量存在差异。氢氧稳定同位素示踪法、镭和氡放射性同位素示踪法、电阻率法、水文地球化学方法各有其优势，针对海岸带类型特点和具体地质、构造及水文地质条件，适宜采用不同方法，或者综合应用多种方法对海岸带的地下水循环和海底地下水排泄进行研究。

关键词：地下水循环；海底地下水排泄；镭同位素；氢氧稳定同位素；电阻率法

Abstract

Coastal groundwater cycle and submarine groundwater discharge is an important part of global water cycle, it recently has been become one of the research focus of land-ocean interactions in the coastal zone. Submarine groundwater discharge is not only a water cycle process but also a geochemical cycle process, these processes deliver massive dissolved material such as nutrients, carbon and metal into the ocean, which plays a significant role in the budget of marine chemical material. The aim of this thesis is to discuss the groundwater cycle characteristics and groundwater discharge into ocean, funded by the province scientific plan of Fujian and the national natural science foundation of China.

This thesis presents the study on the related contents of groundwater cycle and submarine groundwater discharge in the Wuyuan bay of Xiamen, Minjiang estuary and Qianhu bay of Zhangzhou, such as water mass residence time, groundwater discharge flux, recharge relationship of riverine water and groundwater, mixing ratio between groundwater, riverine water and seawater, groundwater cycle characteristics in different aquifers, cause of formation for submarine spring, groundwater cycle model in the coastal zone, which are discussed by the approach of field investigation, sampling, isotope tracer, electrical resistivity detecting and hydrogeochemical method.

(1) Wuyuan bay of Xiamen

Wuyuan bay is a small bay located in Xiamen island, its coast belongs to sandy coast, composed by unconsolidated Pleistocene's marine-alluvial deposit and Holocene's marine deposit. This part focuses on the seawater residence time and groundwater discharge flux in Wuyuan bay.

Based on the difference of 224Ra and 226Ra half life, apparent water age in Wuyuan bay was calculated to be from 0.6~2.4 d, with average residence time 1.4 d and longer residence time in the bay head. This average residence time is

close to 1.2 d calculated by tidal prism approach.

The feature of 224Ra and 226Ra ratio value in groundwater and seawater indicates that 70.2% of groundwater into Wuyuan bay is attributed to the pore water from alluvium, another 20.8% is attributed to the pore water from marine deposit. Through establishing 224Ra and 226Ra mass balance model(box model), 224Ra and 226Ra fluxes driven by groundwater were calculated to be 5.17×106 Bq/d and 5.28×106 Bq/d, respectively. Transformed from these 224Ra and 226Ra fluxes, submarine groundwater discharge fluxes are 4.16×105 m3/d and 4.73×105 m3/d, respectively.

(2) Minjiang estuary

The interaction between riverine water, groundwater and seawater in the Minjiang estuary, where rocky coast and sandy coast coexist, is very clear. Based on field investigation and sampling in dry season and wet season, respectively, relationship between riverine water and groundwater, mixing rate of riverine water and groundwater, mixing ratio between riverine water, groundwater and seawater, and groundwater discharge flux into ocean are key discussion contents of this part.

224Ra and 226Ra desorbing amount from suspending riverine particles increases with increasing salinity, 224Ra and 226Ra basically reach the complete desorption at the salinity of 17.0~18.0. After 224Ra and 226Ra desorbed completely from suspending riverine particles, 224Ra and 226Ra activities in the mixing water exponentially decay with increasing offshore distance, based on this rule, mixing rates between riverine water and seawater in rising tide period were calculated to be 140.2~142.5 m/h.

δ2H and δ18O scatter diagram from water samples better revealed the origin and evolution of groundwater and riverine water, and recharge relationship between groundwater and riverine water. In dry season, groundwater at the south bank of Min jiang river experiences somewhat evaporation after receiving the recharge of rainfall, while groundwater at the north bank of Minjiang river seldom suffer from the influence of evaporation. In wet season, the groundwater at both banks of Minjiang river receive the recharge of rainfall, with slight evaporation. No matter whether dry season or wet season, Minjiang river’s water receive the recharge from both banks of Minjiang river; in dry season, the groundwater at both banks of Minjiang river recharge riverine water after experiencing somewhat evaporation, but in wet season, the groundwater at both banks of Minjiang river rapidly recharge riverine water as soon as it receives the recharge of rainfall.

In wet season, through establishing three end-member mixing model, the mixing ratio between riverine water, groundwater and seawater was calculated to be 34.2%, 10.3% and 55.5%, respectively. Then, based on the monthly average runoff of Minjiang river, groundwater discharge fluxes into ocean were calculated to be 58.1×106 m3/d for the wet season and 7.5×106 m3/d for the dry season, respectively. The former is 7.7 times larger than the latter. According to the groundwater fluxes, the dissolved inorganic nitrogen, reactive phosphate and soluble silicate to the ocean in wet season were estimated to be 12.4×106 mol/d, 0.5×106 mol/d and 10.8×106 mol/d, respectively.

(3) Qianhu bay of Zhangzhou

Qianhu bay is a typical sandy coast, with better developmental sand dune, straighter shoreline, and flat and wide beach, this kind of coast is very suitable to discussing the groundwater cycle. Moreover, submarine spring emerges at the beach of Qianhu bay, which is a rather rare natural phenomenon in China’s coast zone, its origin is a mystery by far. In this part, the characteristics and pattern of groundwater cycle, origin of submarine spring were discussed through investigation and sampling.

Inshore aquifer system constituted by marine deposit and eolian deposit, with better permeability and water-abundance, and rapid water cycle velocity, mainly receives the vertical recharge of rainfall, and its groundwater directly flow into the ocean. Hydrochemical component (Cl/Br, Ca/Mg, Ca/SO4) indicate that the pore water of this aquifer system still partly shows the feature of seawater formed during transgression. The pore water in surface eolian deposit partly presents the feature of seawater influenced by modern seawater. Partial seawater intrusion derived from overpumping occurred at different levels. The pore water from alluvium of coastal plain has obvious leaching and concentration with slow runoff. Fracture-pore water in elurium has different water cycle velocity controlled by local landform, its chemical component varies largely. For the fracture-pore water of Neogene's basalt-sand rock formation, the percentage of milliequivalent of cation Na+Mg2+ and Ca2+ exceed 25% with dominated anion HCO3- show that its water cycle velocity is higher than above pore water of alluvium and fracture-pore water of elurium, which directly related to the elevated landform, developmental vertical fissure in basalt and unconsolidated sand rock.

Electrical resistivity approach revealed that the submarine spring diameter of 5.5 ~6.0 m emerge at the beach, and vertical extending depth is about 2.5~3.0 m at the mouth of spring; the recharge pathway of submarine spring is not perpendicular to the shoreline, but it tends to northwest direction, this direction is consistent with the developmental direction of fault zone formed in Yanshan epoch's intrusive rock.

Some evidence such as the similarity of chemical constituent between submarine spring and fracture-pore water from the Neogene's basalt-sand rock formation, unusually high 222Rn activity of spring water indicate that the recharge area of submarine spring probably comes from the Neogene's basalt-sand rock formation located in Lianhua mountain, and the fracture-pore water of this water-bearing formation recharge the spring through the fault zone of underlying Yanshan epoch's intrusive rock.

The salinity distribution of pore water in the intertidal zone is not very uniform influenced by submarine spring and fresh terrestrial groundwater discharge. The

characteristics of salinity distribution of pore water perpendicular to shoreline indicate that the smaller tidal pump cycle, bigger salt water wedge cycle and fresh terrestrial groundwater discharge together constitute the fundamental water cycle pattern of Qianhu bay, and submarine spring makes this water cycle pattern complicated.

The component of main ions and nutrients of surface pore water(<70 cm) in the intertidal zone show that pore water cycles rapidly, and its geochemical process is simple, chemical reaction is weak, major process is the mechanical mix of fresh groundwater and seawater.

In conclusion, the coastal type of Fujian is more various, different type of coast has different groundwater cycle and submarine groundwater discharge. The different research methods such as tracer of stable hydrogen and oxygen isotopes, tracer of radioactive Ra and Rn, electrical resistivity, hydrogeochemical method, have their own advantages and disadvantages. For the different coastal type and specific geology, tectonic and hydrogeologic condition, single method or multi-method should be suitable to apply in the study on groundwater cycle and submarine groundwater discharge in the coastal zone.

Keywords: groundwater cycle; submarine groundwater discharge; Radium isotope; stable hydrogen and oxygen isotopes; electrical resistivity method

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